Lattice QCD for Hadronic and Nuclear Physics

NCCS USERS MEETING

USQCD Collaboration

Robert Edwards (PI), Balint Joo, David Richards

(*Jefferson Laboratory*)

Robert Sugar (*UCSB*)

Martin Savage (*University of Washington*)

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Project Overview - I

- **USQCD Collaboration is the national collaboration of physicists dedicated to the solution of Quantum Chromodynamics, the theory of the strong interaction of nuclear and particle physics using lattice gauge calculations. LHPC and NPLQCD collaborations focus on structure/spectrum of hadrons and their interactions, respectively.**
- **Lattice QCD enables the *ab initio* calculation of many problems central to our understanding of nuclear and particle physics**

Project Overview - II

- **QCD is a *Gauge Theory*, characterised by local symmetry – c.f. QED**

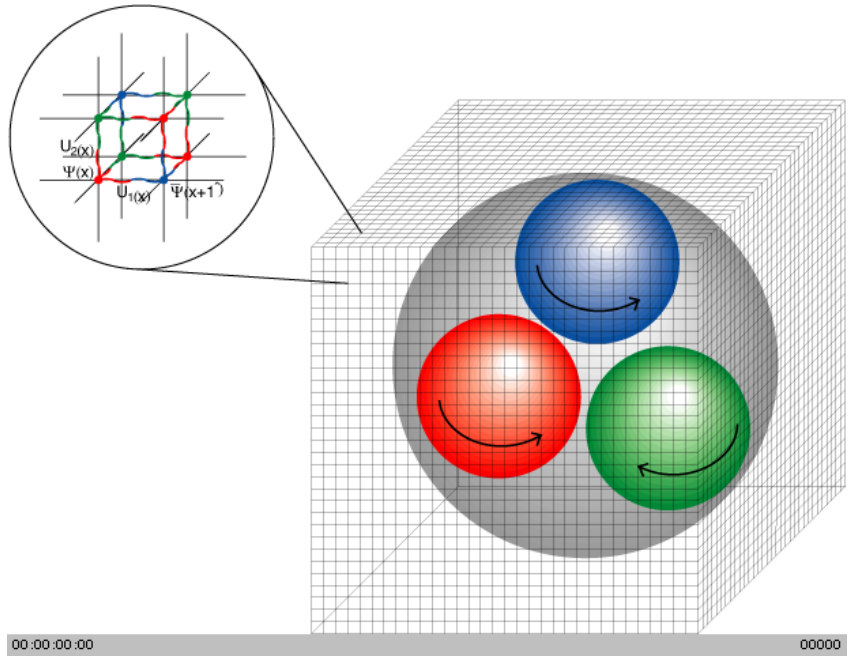
QED	QCD
Photon, γ	Gluons, G
Charged particles, e, μ, u, d,…	Quarks: u, d, s, c, b, t
Photon is *neutral*	Gluons carry *color charge* Theory is *non-Abelian*
α_e ' *1/137*	α_s ' *O(1)*

- **Highly *non-linear theory* – can only use perturbation theory at high energy**

Asymptotic freedom – 2004 Nobel Prize

Project Overview - III

- **Lattice QCD enables us to undertake *ab initio computations of many of the low-energy properties of QCD***
- **Continuum Euclidean space time replaced by four-dimensional *lattice* – current typical sizes $32^3 \times 128$**
- **Computations dominated by *inversion of large, sparse matrices*.**



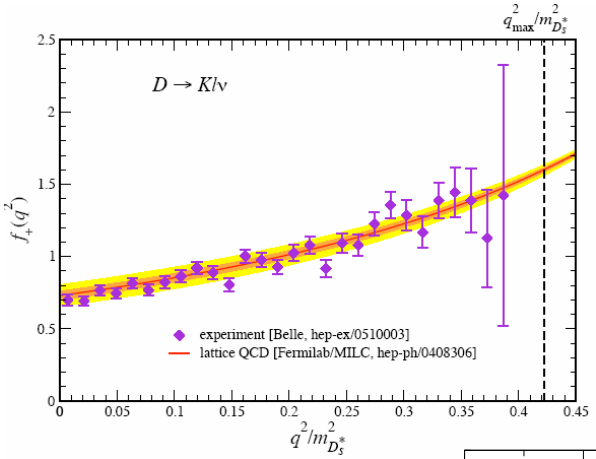
$$3 \times 4 \times 32^3 \times 128$$

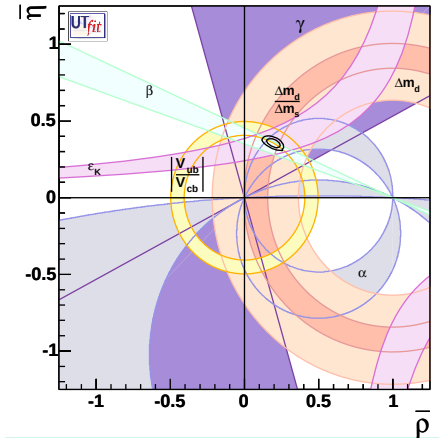
Color spin volume

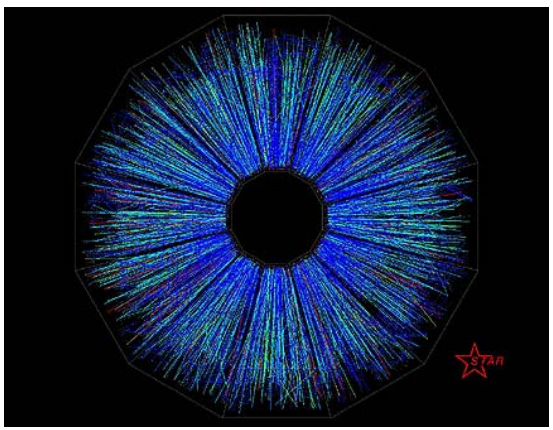
Highly regular problem, with simple boundary conditions – *very efficient use of massively parallel computers using data-parallel programming.*

Project Overview - IV

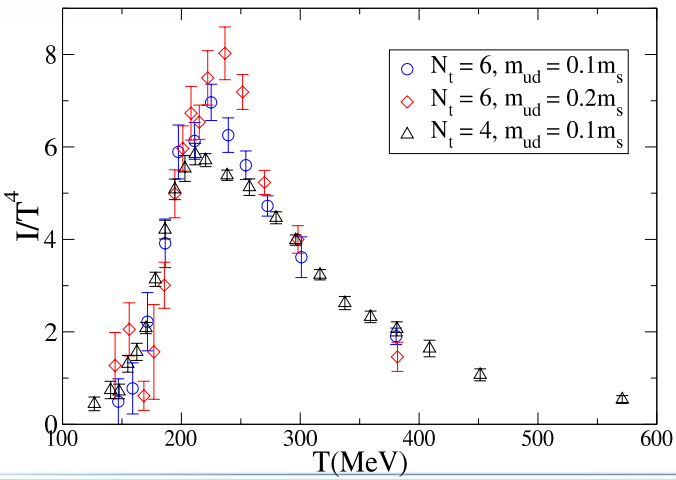
Parameters of Standard Model: FNAL







Behavior of matter under extreme conditions: BNL



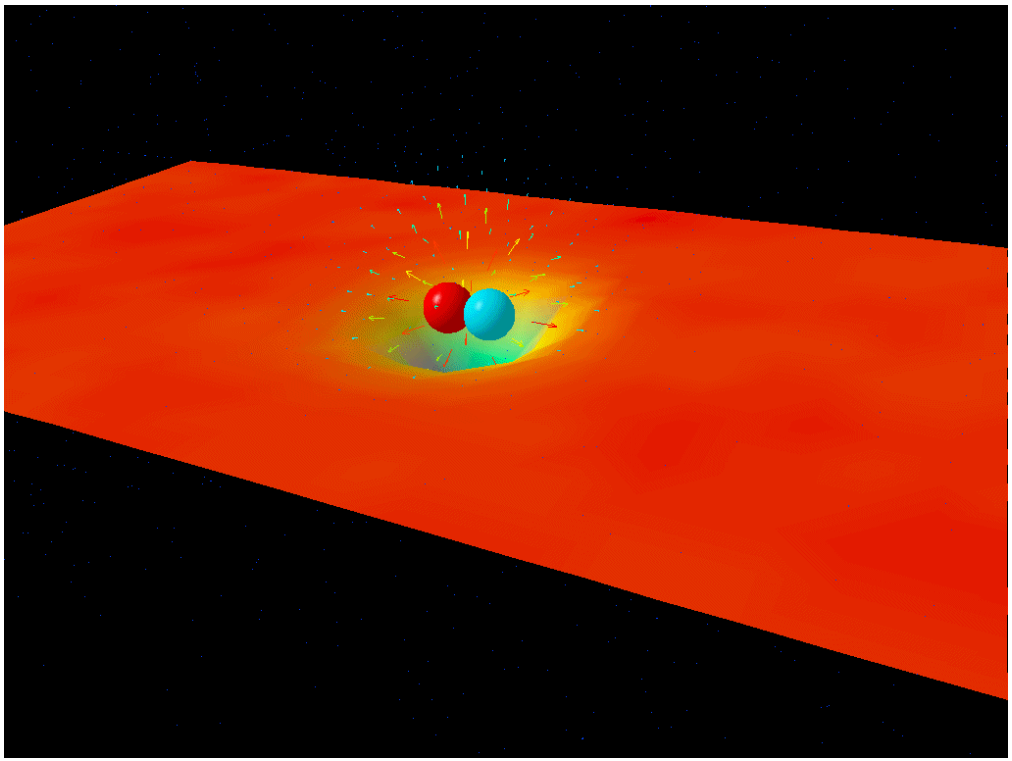
Project Overview - V

- **Generate gauge configurations on anisotropic lattices at light quark masses to enable the spectrum, or excitations, of hadrons and their interactions to be explored. Explore rather than eliminate QCD**

- **Spectroscopy is classic tool for gleaning information about structure of theory**
- **Both experimental and *ab initio* spectroscopy programs aim at *discovering effective degrees of freedom of QCD*, and resolving competing low-energy pictures.**
- **Extend lattice QCD beyond single, isolated hadrons to look at interactions of hadrons and the origin of the nuclear force.**
- **Gauge Configurations can be used across broad swathe of projects in nuclear and particle physics**

Project Overview – VI

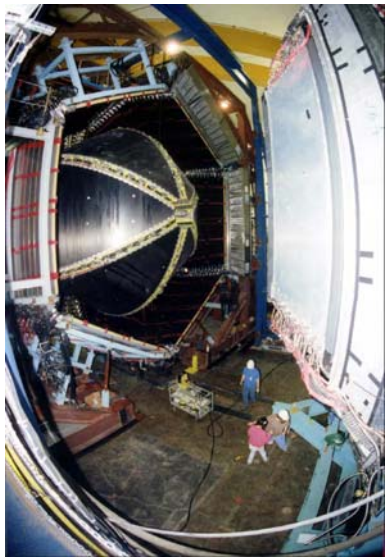
- Visualisations of confinement between a quark and an antiquark by *Derek Leinweber*



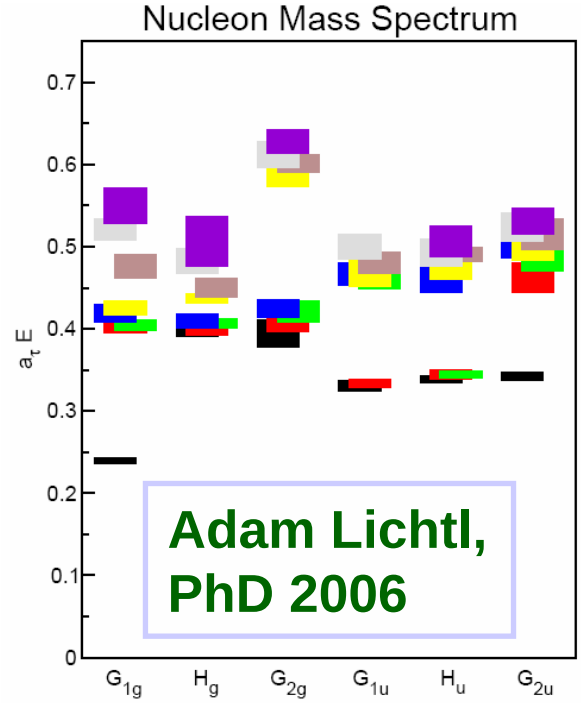
95% of nucleon mass is due to binding of QCD

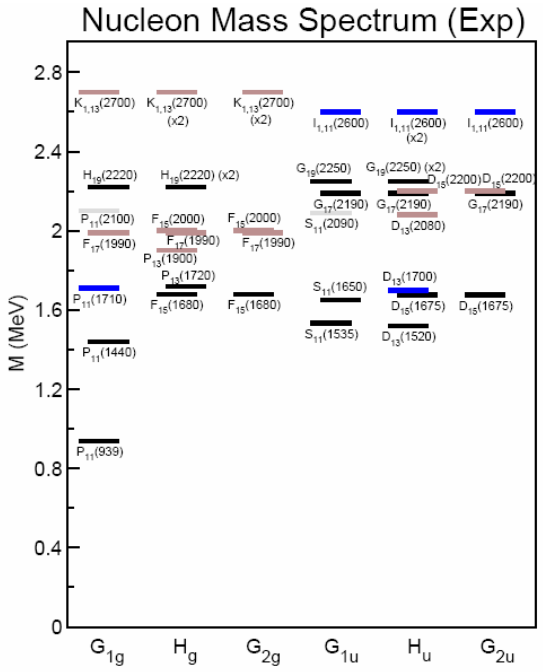
http://www.physics.adelaide.edu.au/theory/staff/leinweber/VisualQCD/Nobel/index.html

Glimpsing the Nucleon Spectrum - I



CLAS Detector at Jefferson Laboratory

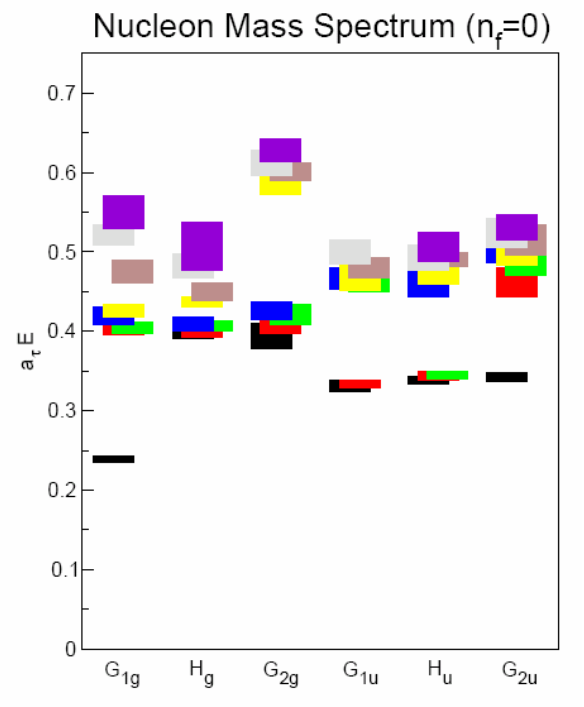


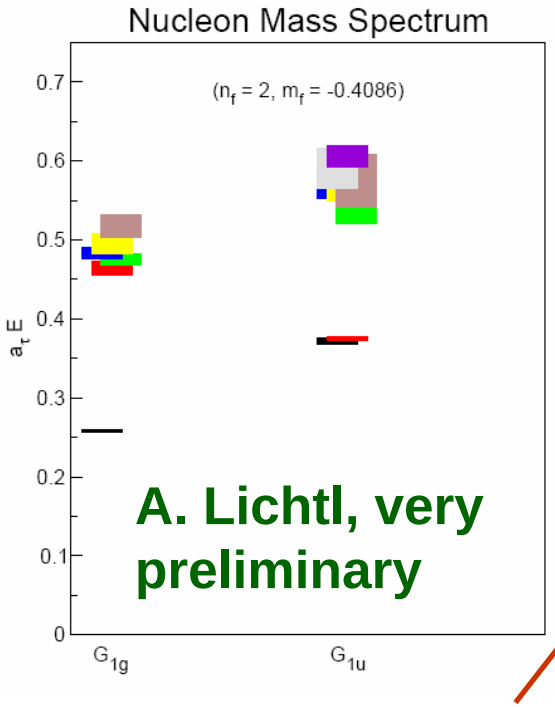


- **Powerful demonstration of our ability to extract as many as eight or nine eigenvalues**
- **Tantalizing suggestions of patterns seen in experiment**

Glimpsing the Nucleon Spectrum - II

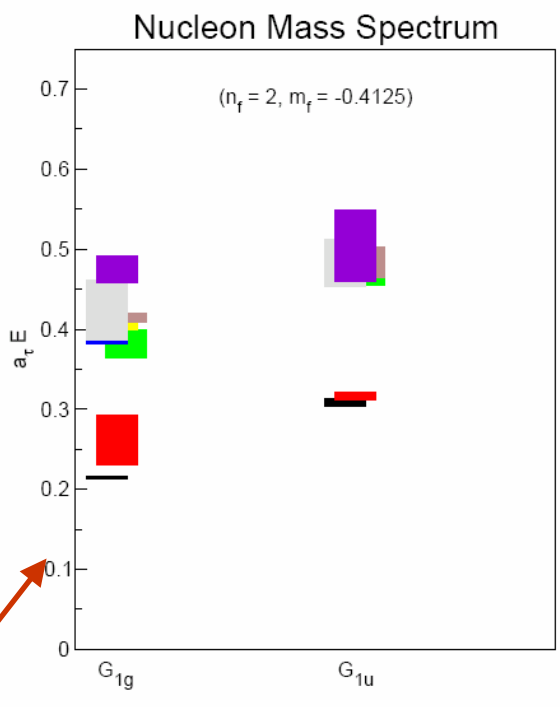
$M_\pi = 647$





A. Lichtl, very preliminary

$M_\pi = 432$

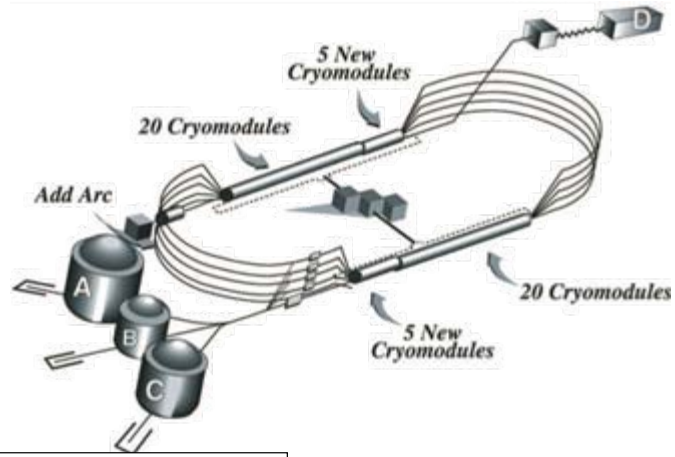


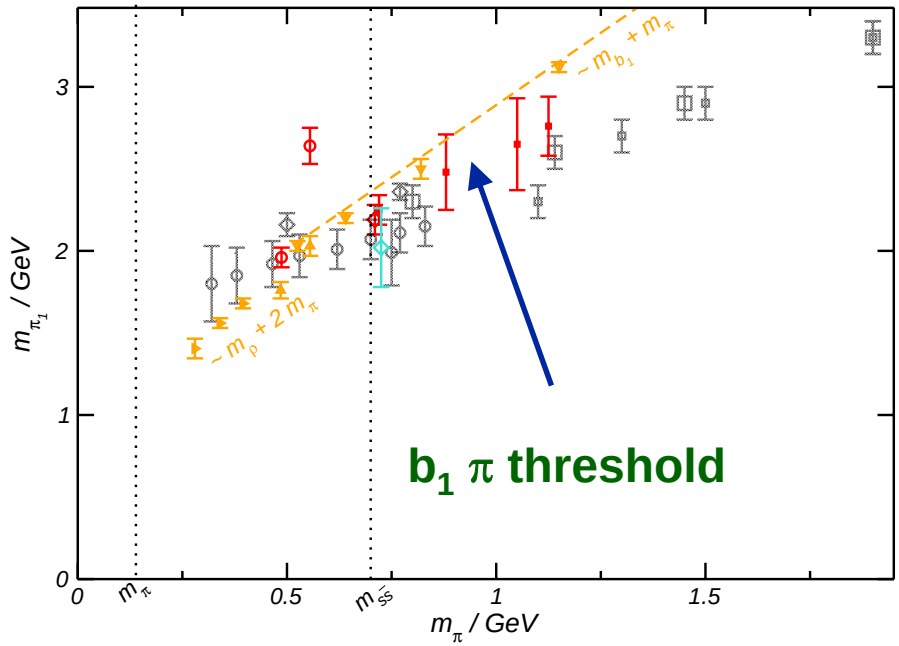
Emergence of Roper resonance at light-quark mass

Hybrid Mesons and GlueX

- **GlueX at JLab aims to photoproduce hybrid mesons in Hall D.**

- **Lattice QCD has a crucial role in both predicting the spectrum and in computing the production rates**



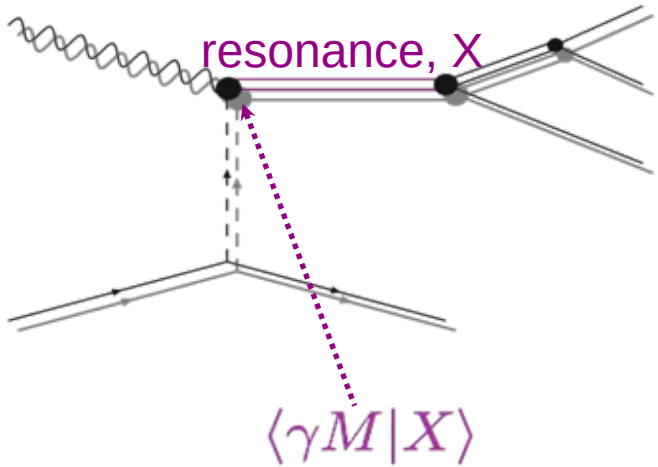


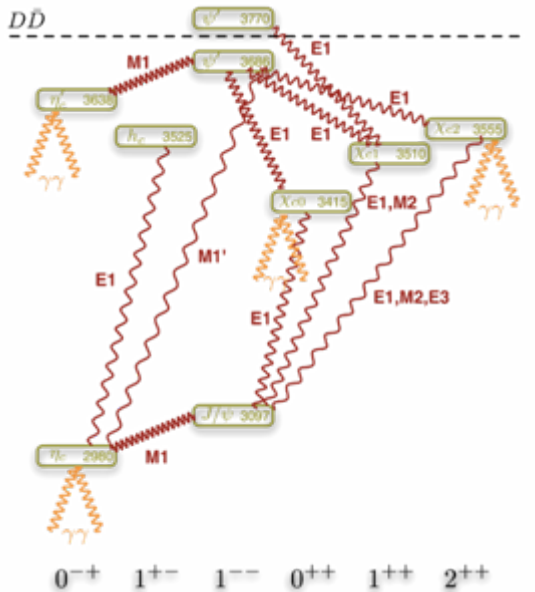
- *MILC qnch Wilson β=5.85*
- *MILC qnch Wilson β=6.15*
- *UKQCD qnch Clover β=6.0*
- *SESAM N_F=2 Wilson β=5.6*
- *MILC qnch Stag.*
- *MILC N_F=3 Stag.*
- *MILC N_F=2+1 Stag.*
- *CSSM qnch FLIC*
- *UKQCD N_F=2 Clover*
- *UKQCD N_F=2 $b_1\pi$*
- *MILC N_F=3 $b_1\pi$*
- *MILC N_F=3 ρππ*

- **Only a handful of studies of hybrid mesons at light masses – mostly of 1^{-+} exotic**

Hybrid Meson Photocouplings - I

- **An important realization of JLab Theorists was that lattice QCD enabled calculation of photocouplings**
- **Guide experimental program as to expected photoproduction rates.**





- **Initial exploration in Charmonium**
  - **Good experimental data**
  - **Allow comparison with QCD-inspired models**

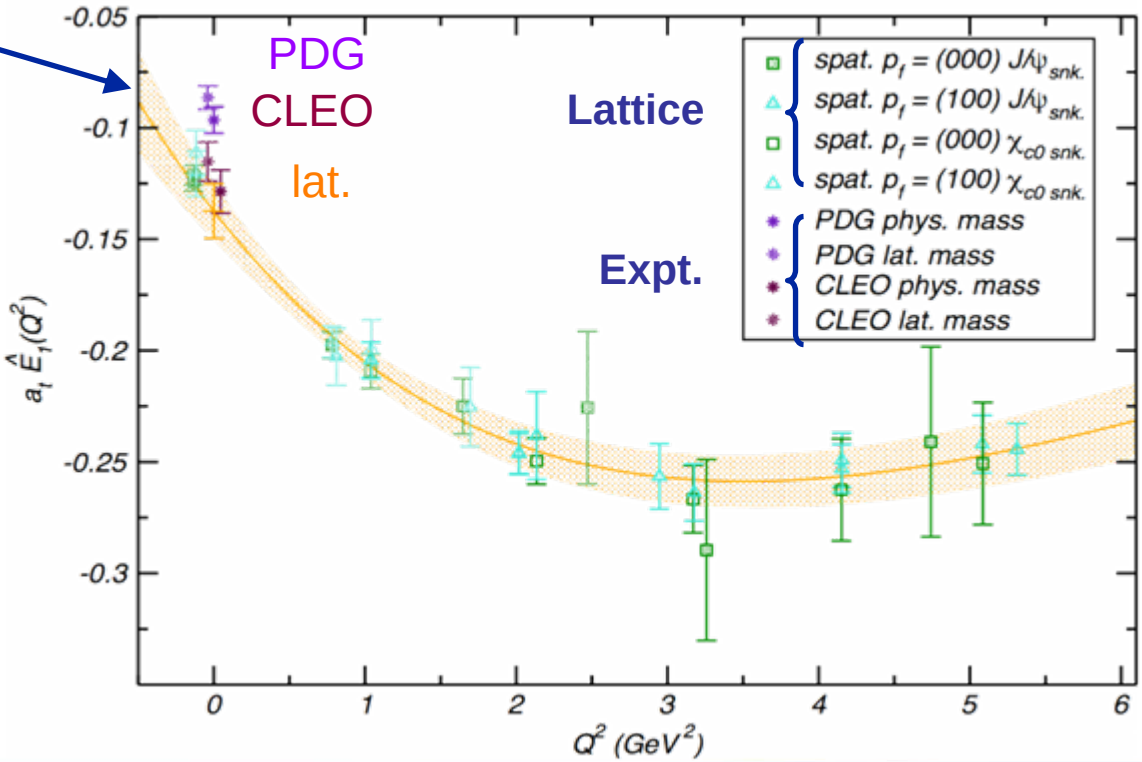
Hybrid Meson Photocouplings - II

Dudek, Edwards, Richards, PRD73, 074507

- Recent study of transitions between conventional mesons, e.g. S ! γ V

$$\Gamma(\chi_{c0} \to J/\psi\,\gamma) = \frac{1}{8\pi}\frac{|\vec{q}\,|}{m_S^2}\,2\,(2e_c)^2\,|\,E_1(0)\,|^2$$

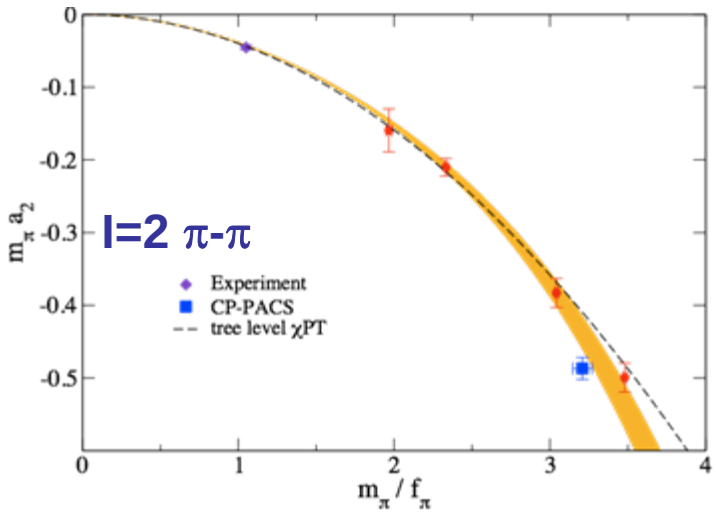
Not used in the fit



Radiative transitions in light-quark sector

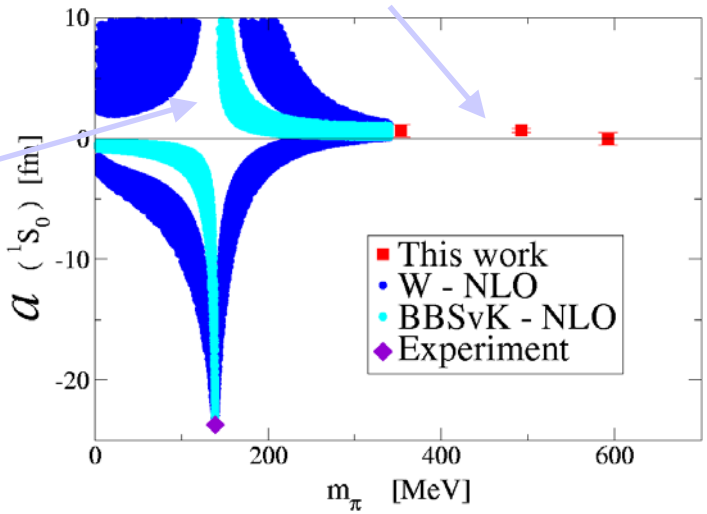
Origins of Nuclear Force

- **Lattice QCD beginning to address nature of origins of nuclear forces**
- **First dynamical calculation of scattering lengths in $^1S_0$ channel and $^3S_1$ - $^3D_1$ coupled channels by NPLQCD (Orginos et al.).**



Current lattice data

ChPT



Computations closer to physical pion mass will enable *ab initio* predictions of scattering lengths

Project Impact

- **Lattice QCD calculation of spectrum of N* resonances essential to complement experimental searches and identify degrees of freedom of QCD**
  - **Excited Baryon Analysis Center (EBAC) at Jefferson Lab**
  - **DOE HP2009 and HP2012 Milestones**
- **Calculation of hybrid-meson photocouplings in light-quark regime essential input to expectations for GlueX Collaboration at JLAB@12GeV**
- **First steps at an ab initio understanding of NN interaction from lattice QCD: HP2014 Milestone**

Project logistics

- **Production**
  - We aim to run 2K core runs for the 24^3x128 lattices and either 2K or 4K core runs for the 32^3x128
  - Our jobs can last a long time 12-24-48h
- **Special Software / Libraries**
  - Libraries: libgmp and libxml2 are useful but we can and do compile them ourselves
  - Compilers: g++ v 3.4.6 would be ideal, but 3.3 will do
  - Threading libraries (for when we go multicore?)
  - Data: we plan to transfer the data off ORNL
- **Visualization**
  - Important for us to consider what to visualize.

Project logistics (continued)

- **Development**
  - Code developed – ready to run - but can be tweaked
    - New algorithms (temporal preconditioning etc etc), improved SSE Assembler, possibly multithreading
    - Most develoment can be done outwith NCCS.
      - Except for the Cray specific stuff.
- **Production Issues**
  - Queue throughput worries (will we get enough to use our allocation ?)
  - SCRATCH space cleaning removing code/data
    - home directory too small to build code in.
- **NCCS Staff Interaction Expectations:**
  - Problem reporting / Some optimization consultancy